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Supply chains' robustness: Challenges and opportunities

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Abstract

Nowadays robustness of supply chains, i.e. their ability to cope with external and internal disruptions and disturbances, gains more and more importance. The paper puts the topic into a broader scope, i.e. it also highlights the concept of robustness in other disciplines (especially in biology) and at the different levels of manufacturing. The main risks of supply chain operations together with some fundamental risk mitigation strategies are summarized. Measures of structural and operational robustness of supply chains are introduced, and the concept of a framework for evaluating supply chains' robustness, complexity and efficiency is described in short. Challenges and opportunities related to the increase of robustness are outlined in the paper, with special emphasis on those which arise in the cyber-physical era.

1. Introduction

Robustness became a fundamental requirement at every level of the production hierarchy from the process / machine level, through the system and enterprise levels, up to the level of supply chains and networks. Before concentrating on the supply chain related issues, in Section 2 the concept of robustness is investigated in biology and in the different domains of manufacturing. The main risk types the supply chains are facing, and some fundamental risk mitigation strategies are summarized in Section 3. Moreover, the structural and operational robustness of supply chains together with some of their quantitative measures are introduced. Section 4 outlines the concept of a framework for evaluating supply chains' robustness, complexity and efficiency in order to achieve trade-offs between these different aspects. In Section 5 the challenges and opportunities the cyber-physical era brings for supply chains' robustness are summarized. Finally, the conclusions are drawn in Section 6.

2. The concept of robustness

The concept of robustness can be found in different disciplines, e.g. in biology, economics, architecture, computer science, systems and control science, and – naturally – in mathematics (e.g. robust optimization).

2.1. Robustness in biology

As to the *biological robustness*: "robustness is a property that allows a system to maintain its functions against internal and external perturbations" [1,2]. "To discuss robustness, one must identify system, function, and perturbations. It is important to realize that robustness is concerned with maintaining functions of a system rather than system states, which distinguishes robustness from stability" [2]. Biological robustness – according to the kind of perturbation – can be classified as mutational, environmental, recombinational, behavioral, etc. one.

It is argued that robustness is a fundamental feature of evolvable complex systems, and evolution enhances the robustness of organisms, e.g. by increasing their complexity through successive addition of regulatory systems. Trade-offs between robustness, fragility, performance and resource demands can be observed in biological systems at different levels. Bacteria, for example, should be able to swim faster without negative feedback, but this would sacrifice their precision in following a chemical gradient: the use of negative feedback improves the bacteria's ability to follow the gradient, at the cost of reduced swim speed [1].

In biology, the following "solutions" are distinguished to ensure the robustness of a system [1]:

- *System control*: negative and positive *feedbacks*, for robust adaptation to perturbations, and for amplification of stimuli, respectively.
- *Alternative or fail-safe mechanisms*: for achieving *redundancy* by several identical or similar components or modules able to replace the one which fails, or by diversity or heterogeneity, whereby a specific function can be attained by other means available in a population of heterogeneous components.
- *Modularity*: for containing perturbations and damage *locally* to minimize the effects on the whole system.
- *Decoupling*: for isolating low level variations from high level functionalities. *Buffers* play a specific role here, e.g. Hsp90 (heat shock protein 90) decouples genetic variations from the phenotype, providing a genetic buffer against mutations.

2.2. Robustness types

The concept of robustness can be categorized by using its different characteristics:

- Robustness *in the small* versus robustness *in the large* depending on the – problem specific – magnitude of the perturbations.
- A similar distinction is made between *local* and *global* robustness, i.e. whether the whole uncertainty space or a relatively limited part of it is considered in the investigations (cp. local versus global optimization).
- *Active* versus *passive* robustness, i.e. whether a modification in the control is necessary or not, in order to preserve the specified properties.
- *Proactive* versus *reactive* robustness, i.e. whether measures are taken before something disruptive happens or after it.

2.3. Robustness in manufacturing

Robustness becomes a more and more important feature at the different levels of manufacturing.

In *product design* robustness is tackled by making the product insensitive to variations, e.g. the environmental variation during the product's usage, the manufacturing variation, and the component deterioration (Robust design or Taguchi method [3]).

A *manufacturing process* is considered robust if it maintains its acceptable performance consistently at a desired level, even if there may be significant and substantial changes occurring in input variables and noise parameters during a given period of time or planning horizon [4]. Naturally, process monitoring and (adaptive) control play a significant role here [5,6]. A comprehensive list and categorization of approaches to measure and evaluate the robustness of manufacturing processes is given in [4].

For a *manufacturing system*, robustness can be defined as the system's aptitude to preserve its specified properties against foreseen or unforeseen disturbances [7].

A fundamental way to increase the robustness of manufacturing systems is to allocate reserves in physical and / or time domains (buffers, inventories or slack times). Another group of approaches relies on different (robust, reactive, predictive-reactive, proactive) scheduling techniques.

Distributed, decentralized control solutions – from their nature – offer higher robustness level for the system. The agent-based, holonic manufacturing systems (HMS) consist of autonomous, intelligent, flexible, distributed, cooperative agents or holons [8,9,10]. The basic approach can be augmented with coordination and control mechanisms inspired by biological systems (i.e. food foraging behavior in ant colonies) supporting the execution of process plans properly under changing conditions, by continuously forecasting the workload of the manufacturing resources and the lead times of the products [9].

The concept of Biological Manufacturing Systems (BMS) aims to deal with dynamic changes in external and internal environments based on biologically-inspired ideas such as self-growth, self-organization, adaptation and evolution [11,12,13]. It belongs to those, more and more frequently adopted approaches which use analogies taken from the biology to develop more effective and robust products and systems.

In [14] the importance of the cooperation between different entities at various levels of manufacturing for realizing more robust and responsive systems is underlined.

3. Supply chains' robustness

3.1. Main risks of supply chain operations

Supply chains are exposed to *risks* of different kinds. *Demand-side*, *supply-side* and *catastrophic risks* are distinguished in [15].

Demand-side risks originate in disruptions emerging from downstream supply chain operations. They can manifest in the physical distribution of products to the end customer (e.g. transportation problems, or improper functioning of the warehouses), or they can come from the mismatch between the forecasted and the actual demands or from the inappropriate supply chain coordination. The well-known bullwhip effect, i.e. the amplification of the demand volatility in the upstream direction of the supply chain is such a characteristic phenomenon. The possible negative consequences of demand-side risks are costly shortages, obsolescence and inefficient capacity utilization.

Supply-side risks include suppliers' business risks, capacity problems, technological changes, product design changes, inappropriate quality of the supply, and poor logistics performance (late delivery).

Catastrophic risks involve natural hazards (e.g. tsunamis, earthquakes, hurricanes, droughts and floods), social-political instabilities, civil unrests, economic crises and terrorist attacks. Because of globe-spanning supply chain operations local problems can greatly affect the performance of whole supply chains.

The main *drivers* of supply chain vulnerability are customer dependence, supplier dependence, supplier concentration (small number of suppliers, or as an extreme, single sourcing), global sourcing (increased uncertainty, poorer transparency and visibility).

3.2. Risk mitigation strategies in supply chain operations

Unfortunately, there is no royal road to mitigate supply chains' risks. In supply chain risk management (SCRM) different approaches are used. Eight mitigation strategies are treated in [16], namely add capacity, add inventory, have redundant suppliers, increase responsiveness, increase flexibility, aggregate or pool demand, increase capability, and have more customer accounts. A further approach which gains more and more significance is the cooperation between the partners.

Making the problem more complex, a mitigation strategy which prospectively handles a certain type of risk may be counterproductive for managing other types. Another important issue to be taken into consideration is the trade-off between efficiency and robustness [17]. This was underlined in Subsection 2.1 dealing with biological robustness.

In the literature, various definitions are given for the *robustness* of supply chains, moreover, some related concepts (resilience, flexibility, changeability, agility, responsiveness, adaptability, etc.) are also in use [18,19].
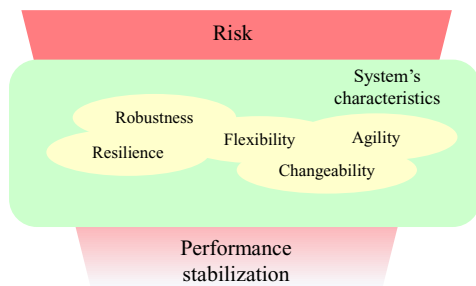
Fig. 1. Relation of robustness, resilience, flexibility, changeability and agility in the stabilization process, i.e. in mitigation of risks [20].

Without going into the analysis of the differences between the formulations given even for the same concept in the literature, and the overlaps between the various ones (see Fig. 1), in the paper the following, more comprehensive formulation is applied: "In the general sense, a supply chain is robust if it is able to comply with the most important key performance indicators (KPI) set towards it, at an acceptable level (i.e. remaining in a predefined robustness zone) during

and after unexpected event(s) / disruption(s) which caused disturbances in one or more production or logistics processes" [21]. Fig. 2 (a further developed version of the figure in [22]) illustrates this concept, also pointing to the possible outcome when the new stable state goes on with an even higher KPI.
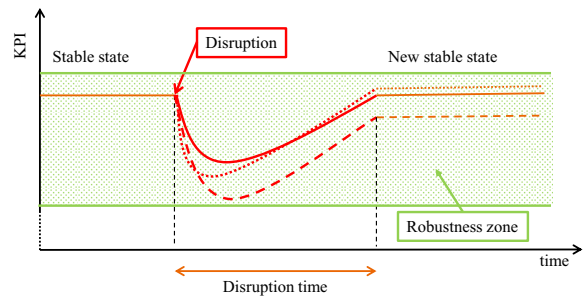
Fig. 2. Delineation of supply chains' robustness used in the paper [21].

3.3. Structural robustness of supply chains and its measures

In the context of supply chains one can speak of *structural (static)* and *operational (dynamic)* types of robustness. In the course of structural investigations, the size of the network, its elements and the linkages between them are put into the focus, while operational investigations deal with the dynamic processes occurring in the supply chains, assuming unchanged structures.

It is straightforward to use *graph theoretical concepts* for characterizing the structural properties of supply chains and networks. Elements (e.g. factories, warehouses, points of delivery) of the chains / networks can be represented by the vertices / nodes of the graph, while the connection of two elements (e.g. a supplier-buyer relationship) by its edges. For describing the relationships in the given field, directed graphs are more adequate than undirected ones.

For the characterization of the vulnerability and robustness of supply chains, the following graph (topological) measures can be advantageously used [21].

Betweenness centrality of vertex *v* (sometimes called *vertex betweenness centrality*) is defined as the proportion of the number of the shortest paths between vertices that pass *v* to the total number of the shortest paths in the graph:

$$BCV(v) = \sum_{u \neq w \in V} \frac{\sigma_{uw}(v)}{\sigma_{uw}}. \tag{1}$$

Here σ_{uw} represents the number of the shortest paths between any vertices *u* and *w* while $\sigma_{uw}(v)$ is the number of the shortest paths within this set, which incorporate vertex *v*. *V* is the set of all vertices in the graph.

In order to compare the betweenness centrality of vertices which belong to graphs of different size, the betweenness centrality values are usually normalized with factors which are somehow related to the size of the given graph. In undirected graphs, an appropriate normalization factor is *(n-1)*(n-2)/2* and in directed graphs *(n-1)*(n-2)*. The value of the normalized betweenness centrality of a vertex lies between *0* and *1*, and

characterizes its importance. (The higher this value, the more important the given vertex, i.e. the graph is more vulnerable here; in other words it is less robust.)

The *edge betweenness centrality* of edge *e* is defined as the proportion of the number of the shortest paths that incorporate the given edge, $\sigma_{uw}(e)$ to the total number of the shortest paths in the graph is also of interest in analyzing supply chains:

$$BCE(e) = \sum_{u \neq w \in V} \frac{\sigma_{uw}(e)}{\sigma_{uw}}. \qquad (2)$$

A relatively new measure for graphs' robustness is *factor R*:

$$R = \frac{1}{n} \sum_{Q=1}^{n} s(Q), \qquad (3)$$

where *s(Q)* is the ratio of vertices in the largest connected subgraph after removing *Q* vertices, to the number of all vertices (order of the graph). (It is always the vertex with the highest degree in the largest subgraph which is eliminated.) The range of possible R values lies in the interval [*1/n, ½*], it is *1/n* in star graphs and *1/2* in fully connected graphs.

Other graph measures which can be considered for describing the vulnerability / robustness of supply chains and networks are: *average path length*, *average shortest distance* and *average clustering coefficient* [23].

3.4. Operational robustness of supply chains and its measures

Operational robustness of supply chains refers to the robustness of the dynamic processes within them, supposing unchanged structures. Perhaps the most important measures of operational robustness are the different kinds of *delivery performances*, or rather the closeness of the performances to their anticipated / planned values. Here, similar measures can be used as in case of manufacturing systems, e.g. the *throughput time* and the *delivery lead time* as measures of the delivery speed, and the *percentage of late deliveries* and the *delivery tardiness* as measures of the delivery reliability [24].

- *Throughput time*: the average time to perform an order from the start of its production to its completion (also referred to as *manufacturing time*).
- *Delivery lead time*: the average time between the placement of an order and its shipment to the customer. (It is worth to mention that – depending on the production planning and inventory policies, and on the actual inventory level – it does not necessarily include the manufacturing time.)
- *Percentage of late deliveries*: the ratio of the number of the late deliveries to the number of all deliveries.
- *Delivery tardiness*: the average time the late deliveries are behind their contractual delivery times, as an indication of the customers' inconveniences.

The above measures can be referred to whole supply chains, but in case of a more comprehensive analysis, they can be used also for every supplier-buyer relationship within them.

As for the characterization of the structural properties the application of the graph theory is the most adequate modelling approach, here the statistical methods come to the front.

4. A framework for evaluating supply chains' robustness, complexity and efficiency

In addition to robustness, in the past years, handling *complexity* gained significant attention also in the production related literature [25,26]. The challenge is to achieve the required level of robustness with the lowest possible level of complexity [21].

The objectivity of the process for evaluating different supply chain settings can be significantly enhanced by using *quantitative measures* of the robustness and complexity. In contrast to most of the papers dealing with the structural properties of supply chains and networks, either from robustness or complexity point of view, in [21] an attempt was made to characterize the structural properties of supply chains and networks from both the aspects of robustness and complexity.

There is an urgent need to investigate the *relation of robustness, complexity and efficiency* of supply chains in order to support management decisions. Fig. 3 illustrates the concept of a framework for evaluating supply chains' robustness, complexity and efficiency.
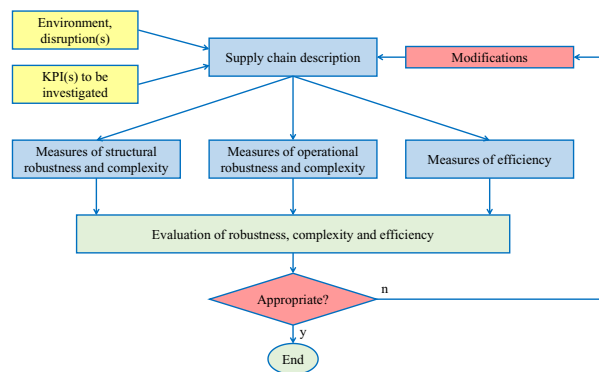

Fig. 3. The concept of a framework for evaluating supply chains' robustness, complexity and efficiency.

The central element of the framework under development is the description of the supply chain to be analyzed (e.g. structure, capacities, orders, production planning and scheduling methods, inventory management policies, etc.), together with the disruption(s) and KPI(s) to be considered. On the basis of the general description, quantitative measures of robustness and complexity both from structural and operational views, moreover, of efficiency are to be determined and the behavior of the selected KPI(s) is to be investigated.

In accordance with Section 3 of the paper, the structural measures rely on graph theoretical considerations, while the operational ones can be determined by analyzing parameters collected from the real system, or by supply chain simulations. Efficiency measures may rely on analytical computations, or even on the simulation results.

In addition to determining the robustness, complexity and efficiency measures of the supply chain under investigation, the framework is intended to serve also for analyzing its behavior in case of different disruptions and disturbances. Moreover, the inclusion of various searching and optimization techniques is also foreseen.

The first results of the – structural – investigations can be found in [21].

5. Supply chains' robustness in the cyber-physical era

Cyber-Physical Systems (CPS) are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its ongoing processes, providing and using, at the same time, data-accessing and data-processing services available on the internet [27,28,29].

Cyber-Physical Production Systems (CPPS), relying on the latest and foreseeable further developments of computer science (CS), information and communication technologies (ICT), and manufacturing science and technology (MST) may lead to the *4th Industrial Revolution*, frequently noted as *Industry 4.0 (Industrie 4.0)* [30]. CPPS consist of autonomous and cooperative elements and subsystems that are connected on the contextual basis within and across all levels of production, from processes through machines up to production and logistics networks [31]. Three main characteristics of CPPS are as follows [31]:

- *Intelligence (smartness)*: the elements are able to acquire information from their surroundings and act autonomously.
- *Connectedness*: the ability to set up and use connections to the other elements of the system – including human beings – for cooperation and collaboration, and to the knowledge and services available on the internet.
- *Responsiveness* towards internal and external changes.

The concept of Industry 4.0 quickly influenced logistics and supply chain management, and new concepts have been established, i.e. *Logistics 4.0* [32], and *Cyber-Physical Logistics Systems (CPLS)* [32,33]. "A cyber-physical logistics system (CPLS) is to be understood as a summarization of primary cyber-physical systems (CPS) which carry out logistics tasks. … Logistics tasks deal in particular with the flow of information and goods in the value chain. CPLS aspire to economic, ecological and social aims" [33].

In the following, some of the main features of CPLS are enumerated together with their potential challenges and opportunities.

- *Internet of things (IoT) and sensor networks*: as a result, better *transparency* can be achieved regarding both the processes within the suppliers (e.g. the readiness level of the orders, the probability and level of the potential late deliveries), and the inter-organizational logistics processes (e.g. the actual geographical position of the transports and their estimated arrival times). The challenge is how to use the available information for decreasing or even eliminating the effects of the potential disruptions and disturbances.

- *Big data and data mining*: the potential is given by the huge amount of data, but the valuable information is usually hidden, consequently, novel *data analytic methods* are to be used. An important question is how to harmonize the *data-driven approaches* with the use of application-dependent, *domain knowledge*.
- *Smart elements with own intelligence*: the resulted *autonomous logistics systems* can show up emergent behavior, consequently, the present control structures have to be replaced with new solutions which are able to handle the distributed settings. Here novel *standards* for information exchange are of fundamental importance.
- *Coupling of the physical and virtual worlds*: the processes can be mapped in the virtual sphere, where, the opportunity for *optimization* arises, on the one hand, by *looking into the future*, i.e. by investigating the consequences of the actual decisions, and, on the other hand, by *learning from the past* based on the stored information. The concept of *digital twins*, or *digital shadows* can play a significant role in the operation of supply chains and the related logistics processes in the near future. However, the importance of the *tight coupling*, i.e. the frequent synchronization of the two worlds is a prerequisite for the successful functioning.

Among the other challenges and opportunities, the realization of more comprehensive supplier management and evaluation, the changing role of the human beings in the complex process of supply chain operation, the potential of a greener logistics, and of novel transportation systems with partially or totally autonomous vehicles can be mentioned first.

As a summary, it can be expected that the cyber-physical solutions – through the quicker and more reliable recognition of the potential external and internal disruptions and disturbances, and through the minimization or avoidance of their negative consequences – will significantly contribute to the better transparency and to the more robust functioning of supply chains. In the cyber-physical era, the complexity of production and logistics systems will increase in parallel with the opportunity for realizing more robust systems.

Consequently, the investigation of the relation of robustness, complexity and efficiency in the field of supply chains will prospectively gain even higher importance in the future.

6. Conclusions

The paper – though focusing on supply chains' robustness – put the topic into a broader scope. It pointed to the fact that the robustness, on the one hand, is present in other disciplines too, and, on the other hand, weaves through every level of the manufacturing hierarchy. It was underlined that the basic principles of the biological robustness can be found in this technical domain, as well.

Different types of robustness exist, e.g. robustness in the small and in the large, local and global robustness, active and passive ones, proactive and reactive ones, and finally, structural and operational robustness, to mention the most important categories only.

An important aspect is that robustness is always *against something*, i.e. a solution cannot be robust against everything. The delimitations of the disruptions and disturbances to be dealt with, and the *KPIs* of interest are of high importance.

Both analytical methods and simulation techniques can find their place in the process of developing robust solutions in manufacturing.

Methods are to be developed and applied for *measuring robustness*, preferably in a *quantitative way*, in order to be able to compare different scenarios and approaches.

Putting the robustness of supply chains into the scope, the main risks of their operations together with some fundamental risk mitigation strategies were summarized. Measures of structural and operational robustness of supply chains were introduced, and the concept of a *framework for evaluating supply chains' robustness, complexity and efficiency* in order to *achieve trade-offs* between the different aspects was described in short.

It was also pointed out that *cyber-physical approaches*, on the one hand, can *increase the robustness* of supply chains, and, on the other hand, they *represent novel challenges* in respect to developing and running robust processes and systems in the CPS era.

In order to realize at least a portion of the sometimes exaggerated expectations towards CPPS and CPLS, significant *further R&D&I* activities are required also in the fields related to robustness.

Acknowledgements

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